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Hybrid thermal lattice Boltzmann model to study the transportation of surfactants contaminated emulsions in parabolic flows

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ABSTRACT

Oil produced from secondary and tertiary processes is mostly in the form of oil in water emulsions, which is an inherent characteristic of the extraction process itself. An attempt to optimize the factors contributing to the cost of transporting such mixtures from the fields to the processing facilities, seems to be very useful and cost effective. In this work, a thorough investigation of the factors influencing the rheology and transportation of emulsions in circular ducts such as temperature, volume fraction, flow driving pressure and surfactants concentration, is performed using a special Lattice Boltzmann model. A dimensionless power number ratio is presented and used for the assessment of the best practices leading to a more efficient emulsions transportation system.

1. Introduction

An emulsion is a mixture of two or more liquids that are immiscible. The dispersed phase exists as droplets in the continuous phase of the emulsion. Surfactants are used to control the size, stability and deformability of droplets. Surfactants also reduce the interfacial tension at the droplet interface, which alters the rheological characteristics of a mixture (Edwards et al., 1993; Langevin, 2014).

Development of surfactants-covered droplets is important for many industries. Several experimental and numerical studies were published on surfactants-covered droplets (Bentley and Leal, 1986; Stone and Leal, 1990; Janssen et al., 1994; Ward et al., 2010; Pawar and Stebe, 1996; Eggleton and Stebe, 1998; Greco, 2002; Saiki et al., 2007; Abbassi-Sourki et al., 2012; Kondaraju et al., 2012). The outcome is that the final morphology of the system helps determining the material mechanical, chemical, thermal and sensory properties of the finished product.

Baret (2012) reviewed interfacial rheology and emulsion properties of surfactants-laden droplets.

Baroud et al. (2010) focused on the pressure fields associated with the presence of the interfacial tension. They found that the interaction between capillary-viscous effects can be dominant in many cases and this interaction grows in unforeseen manner on the scale of the droplet or locally on the interface region.

Ma et al. (2014) investigated the flow topology of moving micro droplets with the aid of micro-particle image velocimetry (μPIV). The authors used different water/oil (W/O) fluid mixtures to see the effects of the droplet geometry, capillary number, viscosity ratio and interfacial tension on the flow topology, internal velocity and circulation.

Schwalbe et al. (2011) reported theory based on isolated spherical droplets in a Poiseuille flow. The model enabled the authors to measure the surface viscous and elastic forces directly from the droplet interface.

Nourbakhsh et al. (2011) used a finite difference scheme to study the motion of three-dimensional deformable droplets in a Poiseuille flow at non-zero Reynolds numbers. They reported that some droplets tend to move towards mid position between the centerline and the channel wall. These droplets proceed like rigid particles and are characterized by a small deformation.

In this work, a special LBM model, which couples the effects of hydrodynamics, interfacial physics, surfactants effects and temperature is used for the investigation of the flow behavior of O/W emulsions with the goal of delineating the best practices for transporting these emulsions in circular ducts. The effects of temperature, flow pressure gradient, volume fraction and surfactants concentration are investigated in a Poiseuille setup. A dimensionless power number ratio was introduced and successfully used for guiding the selection of the most cost-efficient means for transporting O/W emulsion.

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Nomenclature

f^q	collision density distribution function
$f^{q,eq}$	equilibrium distribution function
χ_i	source term
τ^q	lattice relaxation time
ν	kinematic viscosity
μ	dynamic viscosity
Re	Reynolds number
R	density of suspended fluid
B	density of suspending fluid
c_s	speed of sound
δ_t	lattice time
Γ	surfactant concentration
D_s	diffusion coefficient
σ	surface tension
σ_0	clean droplet surface tension
Γ^*	dimensionless surfactants concentration
E_0	elasticity of surfactant
T	temperature
T_0	reference temperature
D_{ifs}	thermal diffusivity
DI	deformation index
u	fluid velocity
$\overline{U}$	average velocity
Δp	pressure difference
P	undisturbed flow power
P_d	droplet power
R_P	power number ratio
F	constant pressure per unit length
Q	volume flow rate
ϕ	flow viscous dissipation
φ_i	volume fraction
φ	dimensionless ratio of energies
R_{ch}	channel radius
R_i	droplet diameter
ℓ_{ch}	channel length
B_o	bond number
We	weber number
Pe_s	Péclet number
γ	interferential tension
g	gravitational acceleration

Subscripts

R	red fluid
B	blue fluid
Eff	effective
X	x-direction
Y	y-direction
Z	z-direction
A	suspending fluid
B	suspended fluid
N	normalized

Superscripts

Eq	equilibrium
T	temperature dependent
W	water
O	oil
E	emulsion

2. Numerical method

2.1. The Gunstensen model

The lattice Boltzmann (LBM) multiphase, single-relaxation model is used in this work. After discretizing the Boltzmann kinetic equation in a finite number of degrees of freedom (DOF), the equation takes the following shape:

$$\widehat{f}_i^q(x, t+\delta_t) = f_i^q(x,t) - \frac{1}{\tau^k}\left[f_i^q(x,t) - f_i^{q,eq}(\rho,\rho u)\right] + \chi_i(x) \tag{1}$$

where f^q is the collision density distribution function, i is the lattice directions, q is used as an index for the two fluids, χ_i is the source term, $f^{q,eq}$ is the equilibrium distribution function, and τ^q is the lattice relaxation time.

A modified Gunstensen multi-component model, capable of tolerating a density ratio up to 20 and high viscosity ratio over 350 between the constituent fluids on the emulsion is used as a basic platform for the proposed scheme. For a smooth transition between the various phases, the interface is considered as a fluid mix and its viscosity is determined by:

$$\nu_{eff} = (\tau_{eff} - 0.5)c_s^2\delta_t = \left(\frac{R}{R+B}\right)\nu_R + \left(\frac{B}{R+B}\right)\nu_B \tag{2}$$

where R and B refer to the density of the suspended and suspending fluids, respectively. For more information about the LBM model used as a base for the proposed scheme, the reader is referred to Farhat et al. (2010).

2.2. The surfactants model

The general time-dependent surfactants convection-diffusion equation is solved by a finite difference scheme, in which the required tangential velocities for coupling the surfactants model with the LBM, are calculated from the fluid Boltzmann model. The surfactants equation is given by:

$$\partial_t\Gamma + \nabla_s\cdot(\boldsymbol{u}_s\Gamma) + K\Gamma u_n = D_s\nabla_s^2\Gamma \tag{3}$$

where $\partial_t\Gamma$ accounts for the temporal change in the interface surfactants concentration, $\nabla_s\cdot(\boldsymbol{u}_s\Gamma)$ is the convection term, $k\Gamma u_n$ is to describe the effects of change in the interface morphology on the surfactants concentration distribution and $D_s\nabla_s^2\Gamma$ is the diffusion term. The coupling back of the surfactants model is implemented through the surfactants concentration effect on the interfacial tension of the droplet. This is implemented by applying the non-linear Langmuir surfactants equation of state:

$$\sigma = \sigma_0\left[1 + E_0\ln\left(1-\Gamma^*\right)\right] \tag{4}$$

where σ_0 is the surface tension of a clean droplet, E_0 the surfactants elasticity and Γ^* is the dimensionless surfactants concentration. For detailed information about the hybrid surfactants model, the reader is referred to Farhat et al., 2011. The presence of the surfactants on the interface prevents the suspended phase from coalescing, through steric repulsion forces. This effect is implemented in the current model by the suppression of coalescence method presented by Farhat and Lee (2011).

2.3. The quasi-steady thermal model

The energy equation used in the thermal model is described by the